PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter II of the Patent Cooperation Treaty)

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference P102426WO	**FOR FURTHER ACTION**	See Form PCT/IPEA/416
International application No. PCT/GB2004/001676	International filing date *(day/month/year)* 19.04.2004	Priority date *(day/month/year)* 17.04.2003
International Patent Classification (IPC) or national classification and IPC G01S5/14		
Applicant SECRETARY OF STATE FOR DEFENCE et al.		

1. This report is the international preliminary examination report, established by this International Preliminary Examining Authority under Article 35 and transmitted to the applicant according to Article 36.
2. This REPORT consists of a total of 9 sheets, including this cover sheet.
3. This report is also accompanied by ANNEXES, comprising:
   a. ☒ *sent to the applicant and to the International Bureau)* a total of 27 sheets, as follows:
      - ☐ sheets of the description, claims and/or drawings which have been amended and are the basis of this report and/or sheets containing rectifications authorized by this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions).
      - ☒ sheets which supersede earlier sheets, but which this Authority considers contain an amendment that goes beyond the disclosure in the international application as filed, as indicated in item 4 of Box No. I and the Supplemental Box.

   b. ☐ *(sent to the International Bureau only)* a total of (indicate type and number of electronic carrier(s)) , containing a sequence listing and/or tables related thereto, in computer readable form only, as indicated in the Supplemental Box Relating to Sequence Listing (see Section 802 of the Administrative Instructions).

4. This report contains indications relating to the following items:

☒	Box No. I	Basis of the opinion
☐	Box No. II	Priority
☐	Box No. III	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐	Box No. IV	Lack of unity of invention
☒	Box No. V	Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐	Box No. VI	Certain documents cited
☐	Box No. VII	Certain defects in the international application
☐	Box No. VIII	Certain observations on the international application

Date of submission of the demand 17.02.2005	Date of completion of this report 06.06.2005
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized Officer Ó Donnabháin, C Telephone No. +49 89 2399-7134

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

International application No.
PCT/GB2004/001676

Box No. I Basis of the report

1. With regard to the **language**, this report is based on the international application in the language in which it was filed, unless otherwise indicated under this item.

   ☐ This report is based on translations from the original language into the following language , which is the language of a translation furnished for the purposes of:
   - ☐ international search (under Rules 12.3 and 23.1(b))
   - ☐ publication of the international application (under Rule 12.4)
   - ☐ international preliminary examination (under Rules 55.2 and/or 55.3)

2. With regard to the **elements*** of the international application, this report is based on *(replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report)*:

Description, Pages

1-31	as originally filed

Claims, Numbers

1, 19-43, 47-62	as originally filed
2-18, 44-46	received on 19.02.2005 with letter of 17.02.2005

Drawings, Sheets

1/6-6/6	as originally filed

☐ a sequence listing and/or any related table(s) - see Supplemental Box Relating to Sequence Listing

3. ☐ The amendments have resulted in the cancellation of:
   - ☐ the description, pages
   - ☐ the claims, Nos.
   - ☐ the drawings, sheets/figs
   - ☐ the sequence listing *(specify)*:
   - ☐ any table(s) related to sequence listing *(specify)*:

4. ☒ This report has been established as if (some of) the amendments annexed to this report and listed below had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).
   - ☒ the description, pages 4,4a,4b,8,9,10,12-17,20,21,23-25,27,28
   - ☒ the claims, Nos. 1,19-43,47-62
   - ☐ the drawings, sheets/figs
   - ☐ the sequence listing *(specify)*:
   - ☐ any table(s) related to sequence listing *(specify)*:

* If item 4 applies, some or all of these sheets may be marked "superseded."

Box No. V Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	2-20,22-28,30-43,46-62
	No:	Claims	1,21,29,44,45
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-62
Industrial applicability (IA)	Yes:	Claims	1-62
	No:	Claims	

2. Citations and explanations (Rule 70.7):

see separate sheet

Re Item I

Basis of the Report

The amendments filed with the letter of the applicant of 17.02.2005 consist of amendments to the description and claims.

1 Description.

The amendments to description are very numerous. Although mentioned as mere corrections of typographical errors in the above mentioned reply of the applicant, it is considered that several of these amendments introduce subject-matter extending beyond the original disclosure (Art 34(2)(b) PCT). The following are examples of amendments extending beyond the original disclosure:

page 14: "provides ZD values for correcting those of the first model .."

page 17: "a grid over the map's coverage region and the models provide the means of working out tropospheric delays .."

page 20: "tropospheric delays vary in accordance with inclination to earth insofar as they are described by ray-tracing that is taking place .."

page 21: "climate model"

page 22: "transmission and reception coding and decoding ..."

No support was provided for such amendments nor could any be found by the examiner. Furthermore, subtle changes have been introduced by the change of "to apparatus in which" to "where" on page 9 and the introduction of "includes" on page 10.

Thus, the examiner has, according to Rule 70.2(c) PCT, proceeded as if the changes to the description had not been made.

2 Claims

For reasons similar to thus expounded to demonstrate the introduction of new subject-matter into the description, the examiner considers that the amendments to the claims also extend beyond the application as originally filed (Art 34(2)(b) PCT). These amendments involve correction of typographical error, changes to the scope of claims and changes to the category of a claim from that of a dependent claim to an independent claim.

The following are examples of extension beyond the originally filed subject-matter:

claim 1: the phrase "presumed by the user to be applicable" cannot be found in the originally filed application documents. Claim 1 contains the phrase "for communication as a correct tropospheric delay value to the user"; the original disclosed claim 1 only mentions "as tropospheric delay corrections".
claims 32, 35, 37, 43: no support found in the description for the changes.
claim 47: no support found for the "plurality of user locations".
claim 59: the phrase "from said delay values applicable to identification signals" lacks support from the description.

No passages from the application as originally filed have been submitted as support for the amendments, nor could any be found by the examiner. Thus, the examiner has, according to Rule 70.2(c) PCT, the examiner has proceeded as if the changes to claims 1, 19-43, 47-62 had not been made.

Re Item V

Novelty, Inventive Step, Industrial Applicability

Given the above mentioned violation of Art. 34(2)(b) PCT, according to Rule 70.2(c) PCT, the examiner has proceeded as if the some of the amendments to claims and description had not been made.

A very complex claim structure arises due to the cancellation of several claims due to extension beyond original disclosure. To make the analysis accessible to the reader, the examiner has drafted the examination Report as follows:

1. Section 3 outlines the substantial objection to lack of conciseness of the present allowable (in the light of Rule 70.2(c) PCT) set of claims.
2. Section 4 comments on the newly filed claims which have not been objected to (regarding Art. 34(2)(b) PCT) in Item I above.
3. Sections 5-8 comment on the originally filed set of claims.

3 Lack of Conciseness (Art 6 PCT)

Claims 1, 2, 43, 44, 45, 59, 61 and 62 do not meet the requirements of Article 6 PCT. Although claims 1, 2, 43, 44 (resp. 45, 59, 61, 62) have been drafted as separate independent method (resp. apparatus) claims, they appear to relate effectively to the same subject-matter and to differ from each other only with

regard to the definition of the subject-matter for which protection is sought and in respect of the terminology used for the features of that subject-matter. The aforementioned claims therefore lack conciseness. Moreover, lack of clarity of the claims as a whole arises, since the plurality of independent claims makes it difficult to determine the matter for which protection is sought, and places an undue burden on others seeking to establish the extent of the protection.

4 Comment on allowable claims filed with letter of 17.02.2005

4.1 Independent claim 2 lacks clarity (Art. 6 PCT) as it does not contain the technical features of the invention (Rule 6.3(a) PCT). The claim relates to a method of obtaining tropospheric delay data. It appears that the tropospheric delay corrections are sent to the user. There is no indication given as to how tropospheric delay data can be derived from tropospheric delay corrections. The claim thus lacks clarity.

4.2 Independent claim 44 is considered to lack novel subject-matter (see paragraph 6.2 below).

5 Documents Considered in Examination

The following documents are cited in this Report:

D1: US2002/0199196 (M. Rabinowitz, J.J. Spilker) 26.12.2002

D2: B.W. Parkinson, J.J. Spilker "Global Positioning System: Theory and Applications, Volume 1", pages 517-546

6 Novelty (Art. 33(2) PCT)

The subject-matter of claims 1, 21, 29, 44, 45 lacks novelty.

6.1 Document D1 discloses the following features of independent claim 1:

-1-. A method of obtaining tropospheric data for use in a satellite positioning system or GNSS (**see D1, paragraphs 0051-0053, paragraph 0051, first**

sentence) comprising the steps of:

-2-. generating for a user location, at a location remote from the user location and from meteorological information (**see D1, paragraph 0038;** *Although 0059 relates to an embodiment where the position calculation is carried out in a location server, rather than in the mobile, it is clear that the location server 110 which calculates the tropospheric corrections is the same for both embodiments*)

-3-. at least one accurate tropospheric value applicable to the user location (**see D1, 0038**)

-4-. for communication as a tropospheric delay correction to a said user (**see D1, paragraph 0051**)

The contribution above the prior art D1 of the subject-matter of claim 1 is that claim 1 mentions **tropospheric delay data** where D1 mentions **tropospheric velocity data.** It appears however, that the authors of document D1 intended to employ **tropospheric delay data** rather than **tropospheric velocity data.** This is borne out by the fact that D2, (referred to in paragraph 0038 of D1 as the source for algorithms for calculating the tropospheric velocity) only divulges models for determining the tropospheric zenith delay data in the GPS context and makes no reference to tropospheric velocity data. Moreover, paragraph 0042 of D1 makes the simple comment that the pseudo ranges are corrected according to the tropospheric propagation velocity. Were the pseudo ranges to be corrected by delay corrections, this would entail a very simple process. However, correcting pseudo ranges using propagation velocity information would be a formidable task. Thus, the examiner considers the disclosure of D1 to be, in fact, an anticipation of the subject-matter of claim 1, and thus, that this claim lacks novel subject-matter.

6.2 The above argumentation can also be employed to demonstrate the lack of novel subject-matter of independent claims 44 and 45.

6.3 Document D2, page 541 describes determining accurate tropospheric delay value by ray tracing techniques (claim 21).

6.4 The user terminal of D1 receives tropospheric propagation velocity data from the location server (**see D1. paragraph 0051**). Interpreted, as above, that in D1 tropospheric delay data was intended, D1 discloses that features of dependent claim 29.

6.5 D1, paragraph 0051 discloses the features of claim 24.

7 Inventive Step (Art. 33(3) PCT)

Claims 19, 20, 22, 23, 25, 26-39, 46 lack inventive subject-matter.

7.1 The objection to lack of clarity below notwithstanding, it appears that dependent claim 19 lacks inventive subject-matter. As the tropospheric corrections are calculated on the basis of air temperature, etc. in the vicinity of the user terminal, it is clear that an estimate of the location of the receiver is required. Moreover, the majority of the algorithms for calculating tropospheric delay data require a knowledge of the zenith angle, thus, requiring an estimation of the location of the mobile unit.

7.2 The feature of claim 20 where the position is provided by the user is considered common place, and thus lacking in inventive step.

7.3 D1, paragraph 0038 mentions that the weather information is available over the internet and from other sources such as the NOAA. As this information is more than likely determined by numerical forecasting, dependent claim 23 cannot be consider as involving an inventive step.

7.4 Claims 22, 25, 26-39, 46 do not contain any inventive subject-matter.

8 Clarity (Art. 6 PCT)

The claims are considered to lack clarity (Art. 6 PCT). In their present formulation it is very difficult to ascertain how the steps of the methods (in claims 1-44) are interlinked, and how they relate to the disclosure of the description (Art. 5 PCT).

8.1 The terms "said meteorological model" and "said various user geographical locations" in claim 2 lacks an antecedent definition. It is not clear from claim 2 as for which subject "it" is the replacement pronoun.

8.2 Claim 19 makes reference to "said derivation". However, "said derivation" lacks an antecedent definition.

8.3 There seem to be errors in the wordings of claims 47 and 59. Claim 47 (second line) contains the token "applicable to from", while claim 59 (third line) contains the token "values and from and delay values".

9 Synopsis/Suggestion

It appears that the third aspect of the invention (independent claim 59) relates to a receiver and its mode of operation which is not anticipated by the prior art. Having a receiver with an on-board model for deriving tropospheric data and obtaining corrections to these values from a much more accurate model (which employs meteorological measurements and takes the position of the receiver into account) from a reference station reduces greatly the amount of data which the reference station would otherwise be required to send to ensure the calculation of a position of the receiver with equal accuracy.

10 Further Defects of the Application

10.1 The independent claims are not in the two-part form in accordance with Rule 6.3(b) PCT, which in the present case would be appropriate, with those features known in combination from the prior art (document D1) being placed in the preamble (Rule 6.3(b)(i) PCT) and with the remaining features being included in the characterising part (Rule 6.3(b)(ii) PCT)

10.2 According to Rule 6.2(a) to include reference signs should be inserted in the claims to facilitate quicker understanding.

communication systems that are available to mobile users and the limited capacity for processing within a reasonable amount of time.

D1 describes a system for determining the position of a user terminal, which acknowledges that in certain locations, notably urban areas, satellite signals are poorly received in comparison to broadcast terrestrial television signals, and proposes a location determining system comprising a GPS or analogous receiver that employs reception of signals from an array of surrounding television broadcast transmitters at fixed positions instead of, or in addition to, signals from orbiting satellites when signal propagation conditions favour use with the former. Insofar as such terminals are known per se that determine from signals received from spatially separate sources pseudorange signals to the sources from which they compute position, D1 describes two new forms, a first wherein the position of the user terminal is determined in a server located remotely of the user and the user terminal position transmitted to the user terminal, and a second form wherein the position of the user terminal is determined within the user terminal using data in signals received from orbiting satellites or terrestrial TV signals and data transmitted from a remotely located server.

The first method involves transmission of pseudoranges, computed in the user terminal from received signals, to the remote location server and the location server solves the simultaneous equations that use the pseudoranges to define the user terminal position. To do so, D1 also discloses that the location server receives meteorological information relating to the location (vicinity) of the user terminal from which information the location server determines tropospheric propagation velocity applicable to the satellite signals received at the user terminal before being forwarded to the location server, and modifies the pseudorange values for computing the user terminal position to achieve greater positional accuracy .

The second method involves transmission of data to the user terminal from the location server to enable the user terminal to determine its own position, one of the data transmissions being tropospheric propagation velocity computed from inter alia meteorological information accessed by the location server so that the user terminal

can better determine its position. D1 does not disclose how the user terminal differs in form when receiving this additional data or how the data is put to use.

Such transmission between the location server and user terminal are local transmissions via a telephony network. In each case there is considerable data to transfer, whether comprising a plurality of pseudorange signals or propagation velocity computations for any of the posible locations the user terminal may be at.

The present invention provides a method of obtaining tropospheric delay data for use in a satellite positioning system or GNSS comprising the steps of generating for a user location, at a location remote from the user location and from meteorological information, at least one accurate tropospheric delay value, applicable to the user location for communication as a tropospheric delay correction to a said user.

Preferably said accurate tropospheric delay values are derived by a ray tracing technique. The accurate tropospheric delay values may be derived by three-dimensional refractive index field generation. Furthermore, it is also preferred that said meteorological information is based on numerical weather prediction (NWP) data.

In one implementation of the invention applicable to a user whose position is not accurately known, the method may comprise generating, from a first model which is known per se, a first set of approximate tropospheric delay values applicable to various user geographical locations, generating from a meteorological model employing such meteorological information a second set of tropospheric delay values that are accurate and applicable to said various user geographical locations, developing a set of delay value modifications for use with said first model so that the first model can provide a set of tropospheric delay values substantially in agreement with the second set, and expressing the set of modifications as a set of tropospheric delay corrections for communication to a said user.

The first model is based on non-meteorological parameters, which parameters comprise at least one of time of year, latitude and altitude. The non-meteorological

parameters may further comprise at least one of longitude and time of day.

The meteorological model or each said tropospheric delay value correction derived therefor may be augmented by directly observed meteorological data.

In the method of this embodiment the first and meteorological models develop sets of tropospheric delay values comprising zenith tropospheric delays. The first model may

Such communication may be to an orbiting satellite and the members re-transmitted one at a time as the time for which each was predicted becomes current in respect of the forecast.

A second implementation of the method is applicable when the position of the user receiver with respect to the server and/or GNSS satellites is known. That information may be employed by the server with the meteorological information to derive actual or mapped tropospheric delay values (rather than zenith delay values) for communication to the user for the purpose of setting or correcting the user receiver pseudoranging and obtaining accurate timing values. Such communication may be direct or via a network. It may also take place via one or more satellites, such as the GNSS satellites as discussed above, although data reduction may be required. Insofar as the users location is known, it is not expected to be necessary to derive and communicate a set of delay value corrections representing a distribution over a region. However, as discussed above, it may be appropriate to forecast weather conditions for any user location the user may be in and derive a predicted set of delay corrections and communicate these in batch form for use by the user receiver in turn as the time for which each member was predicted becomes current.

According to a second aspect of the present invention there is provided apparatus for obtaining data for use by a user of a satellite positioning system or GNSS, comprising generating means for generating, at a server location remote from the user from meteorological information, at least one accurate tropospheric delay value applicable to the user location and means to communicate at least a function of a said value to the user as a tropospheric delay correction.

The server may be arranged to derive a set of tropospheric delay values applicable to a plurality of user locations.

In a first embodiment of the invention, the apparatus of the preceding paragraph comprises first generating means for generating a first set of approximate tropospheric delay values from a first model which is known per se, second generating means for

generating a second set of more accurate tropospheric delay values from a said meteorological model based on meteorological information, and developing means for developing from said first and second delay sets a set of tropospheric delay value modifications for use with said first model so that it can provide a set of tropospheric delay values substantially in agreement with the second set, and said developing means being arranged to express the modifications as a set of tropospheric delay corrections.

Preferably said first generating means utilises a said first model is based on non-meteorological parameters. Also, the developing means may be arranged to express said set of corrections each as a difference between corresponding values of the first and second sets, possibly as a fractional change from the values to be corrected.

The developing means is arranged to express the corrections as a distribution over a region of the earth's surface, preferably in the form of a data file corresponding to a greyscale image of multi-bit words, each word representing a location of the region. Furthermore the apparatus may include means for compressing said set of corrections. This may effect lossless compression of the set or for greater reduction, lossy compression on the set.

Each of the first and second generating means may advantageously derive corrections for parameters of at least an elevation mapping function used to map the zenith delay values to actual delay values. Corrections may be superimposed on the zenith delay correction data set as longer words for communication to the receiver

The apparatus also transmission means for transmitting said set of corrections to a user, and preferably to transmit via an orbiting satellite, which may be a satellite of the GNSS.

In a second embodiment, applicable where the position of a user receiver of satellite signals is known, apparatus is arranged to receive from the user information defining at least one of the user location with respect to the server or with respect to the GNSS satellites and to provide corrections in the form of tropospheric delay values per se

rather than zenith delay values, although the latter could be provided .

According to a third aspect of the invention a GNSS user receiver comprises means operable to generate from an on-board model from non-meteorological data a set of approximate tropospheric delay values applicable to identification signals received from a plurality of said satellites and from said delay values and identification signals received from a plurality of said satellites compute an approximate position of the receiver relative to the earth's surface or time, means operable to receive a set of corrections to said tropospheric delay values derivable from the model, said corrections being derived from meteorological data, means to effect modifications to said derived delay values in accordance with the corrections and means to compute the position or time with greater accuracy.

Said means to effect modification to said delay values may be operable to effect interpolation or extrapolation of said corrections according to computed position of the user relative to locations for which the corrections have been derived.

According to a fourth aspect of the invention a GNSS including a plurality of orbiting satellites, includes apparatus as defined above for obtaining data and a user receiver.

In the above discussion, tropospheric delay values and zenith tropospheric delay values have been referred to without regard to their nature. Whereas it is possible to derive a single tropospheric delay value for a particular position, it is more usual to derive it as a so-called "wet" delay and a "dry" or "hydrostatic" delay. Apart from circumstances where it is important to distinguish, in particular in respect of data reduction, in this specification, references to tropospheric delay or delays and their derivation is intended to be read as deriving values for each.

Further details and advantages of the invention will be evident from the following description with reference to the following drawings, in which

Figure 1 is a schematic representation of a GNSS positioning system known from the art, illustrating a user positioning receiver device and a plurality of orbiting

compromised by delays inflicted upon the signals by refraction in the troposphere caused by refraction, principally the water content of meteorological systems such as weather fronts. Such tropospheric refraction may be compensated for, at least to a first approximation, by applying to processing of the received signals a first model 130 that represents climatic conditions anticipated for that approximate location at the time of year. This so-called climate model is essentially non-meteorological, insofar as it is updated infrequently and represents at best a representation of average conditions. In known manner the climate model 130 holds parameters for at least one, and preferably all of time of year, latitude and altitude as pertain to the position of the user and may optionally hold parameters of longitude and/or time of day.

This first, climate model is arranged to generate zenith tropospheric delays (ZD) that may be applicable to the users location that may be mapped in respect of satellite elevation inclination with respect to the receiver to give a more accurate value of tropospheric delay and effect pseudorange corrections having regard to the direction actually taken by the received signal path, particularly if the satellite is at low elevation.

To this end, the first model may include an elevation mapping function 130' employing, for example a three-term continued fraction approximation, substantially as set out by Niell in the paper mentioned above. However, it should also be understood that the parameters used in the mapping model, being derived from the time of year, latitude and altitude parameters mentioned above, are also subject to errors caused by meteorological disturbances, although for many purposes these errors may be considered too small to correct.

This prior art apparatus utilises the zenith tropospheric delay, and if appropriate a mapping function, to effect an approximate correction to the tropospheric delays enabling the receiver to compute a more accurate solution for position and time.

Notwithstanding its inherent inaccuracies, this first model is valuable insofar as it permits a user receiver to be manufactured and used with this (albeit limited) correction facility built in and not dependant upon receiving signals from elsewhere.

Hitherto, the positioning accuracy of a user receiver has been compromised by a number of factors but as these resolve, and error sources reduce, it is apparent that residual tropospheric delay errors that remain after using the first model are now an important cause of limitation to accuracy.

Referring now to Figure 2, in accordance with the present invention there is provided at an earth location a ground station 200, conveniently referred to herein as a server, although there may be more than one associated with different regions of the earth's surface. This server has no means for receiving satellite signals but is coupled to receive from one or more meteorological organisations information representing the results of, or suitable for, numerical weather prediction (NWP) for locations at various positions around the earth; the meteorological information may be global in nature or confined to one or more sub-global regions.

There is provided in the server, and indicated at 230, a duplicate of the first model (130) as used in the user receiver, which contains the aforementioned non-meteorological, climate modelling parameters.

There is also provided in the server a second, or meteorological, model indicated generally at 250. This model responds to meteorological information provided by the NWP and determines accurate values for ZD (as wet and dry components).

The zenith tropospheric delay (ZD) values for the two models are compared at 260 in order to determine differences between them that constitutes an error attributable to the first model. The differences thus constitute modification values by which the product of the first model might be modified or corrected in order to provide the same result as the second model.

These corrections are encoded and subjected to data reduction at 270, as described in detail below, and then communicated to the user receiver by way of a communication channel 280 that constitutes an uplink to one or more of the GNSS satellites 110_1 etc by way of transmitter 275 and re-transmission from the satellite or satellites to the user receiver, indicated generally at 220.

The user receiver includes a decoder 228 of the correction values data that thus provides ZD values for correcting those of the first model (wet and dry values) effectively making them the same as if derived accurately by the second model present only in the remote server, for use in the navigation and time computing.

Optionally, as also described below, the corrections may include items applicable to mapping functions of the first model so that both zenith delay and mapping function values are given a greater accuracy for the position and time computation.

The above overview of the system is expanded below with discussion of further features that can be employed individually but which when used together interrelate advantageously.

Referring to the server 200, the meteorological model relies upon a three-dimensional array of grid points for which meteorological information is available and uses such information to derive a refractivity field that permits ray tracing between a ground point near the earth's surface and a particular satellite, as a result of which a tropospheric delay value (for each of the wet and dry delays) can be found.

At this point it is appropriate to give some background on propagation and atmospheric refractivity and atmospheric effects as they relate to ray-tracing and NWP.

The speed of propagation of an electromagnetic wave through a medium can be expressed in terms of the refractive index, n, defined to be the ratio of the speed of light through free-space to the speed through the medium (Equation 1-1).

$$n = \frac{c}{v} \qquad (1\text{-}1)$$

where:

n is the refractive index

c is the speed of light in free space

v is the propagation velocity

In practice, and as illustrated in Figure 3(a), a satellite signal path is curved by

refraction as it passes between the satellite and earth, most of this in the troposphere and manifested as a delay. The GNSS tropospheric time delay, ignoring relativistic effects, is defined to be the propagation time of the GNSS signal from the satellite to the user minus the free space propagation time:

$$d_{trop} = \int_{\text{User}}^{\text{SV}} n(s)\, ds - \int_{\text{User}}^{\text{SV}} ds \qquad (1\text{-}2)$$

where:

s is the distance along the propagation path.

The first integral is along the curved propagation path; the second integral is along a geometric straight path.

The differential equation describing the curved ray path can be expressed, in cartesian coordinates, as:

$$\frac{d}{ds}\left(n\frac{dr}{ds}\right) = \nabla n \qquad (1\text{-}3)$$

where $\boldsymbol{r} = \boldsymbol{r}(s)$ is the vector describing the ray path,

s is the length of the curved ray path up to $\boldsymbol{r}$,

$\boldsymbol{n}$ is the refractive index scalar field,

$\nabla \boldsymbol{n}$, a vector field, is the gradient of $\boldsymbol{n}$.

The differential equation can be expanded as

$$\frac{d^2 r}{ds^2} = \frac{1}{n}\left(\nabla n - \left(\nabla n \cdot \frac{dr}{ds}\right)\frac{dr}{ds}\right). \ (1\text{-}4)$$

A first order ordinary differential equation (ODE) with known initial values can be solved using numerical methods: for example Runge-Kutta or Adams-Moulton methods. Higher order differential equations can be solved numerically by rewriting them as an equivalent system of first order equations. Using the substitution $\boldsymbol{r}_1 = \boldsymbol{r}$ and $\boldsymbol{r}_2 = \mathbf{r}'$ (the first derivative), the ray path differential equation (1-4) can be expressed as an equivalent system of two first order differential equations 1-5 and 1-

6:

$$r_1' = \frac{dr}{ds} = r_2 \qquad (1\text{-}5)$$

$$r_2' = \frac{d^2 r}{ds^2} = \frac{1}{n}\left(\nabla n - (\nabla n . r_1') r_1'\right) \qquad (1\text{-}6)$$

The determination of the ray path therefore amounts to the solution of a system of two ODEs with initial values. Standard numerical methods can be used to solve the problem: for example, a Runge-Kutta method with adaptive step control consistent with user defined tolerances.

With the ray path solved, the tropospheric delay can be computed as:

$$d_{trop} = \int_a^b n(s)\, ds + \int_b^c ds - \int_a^c ds \qquad (1\text{-}1)$$

where a, b and c are as shown in Figure 3(a). Point b corresponds to the point at which ray curvature and refractivity can be assumed to be negligible, in this specification above an altitude of 70km.

The ray-tracing process to determine the path from user to satellite (a to b to c in Fig. 3(a)) starts at point a and assumes a starting elevation angle of $\alpha_{Apparent}$. Although the precise satellite position and therefore α_{True} is known, $\alpha_{Apparent}$ (such that the ray path intersects point c) can initially only be estimated. Because ray tracing starts off at an angle that is at best a guess, the resultant ray path will in general not intersect point c. By deriving at least two ray traces and using interpolation or iterative methods it is possible to establish an angle of suitable accuracy from which tropospheric delay is derived. The present invention is predicated upon deriving for use a more accurate value for each tropospheric delay.

At least part of tropospheric delay determination is based upon Numerical Weather Prediction (NWP) modelling which forecasts the evolution of atmospheric physical

processes by applying governing equations, including the conservation of mass, momentum and energy. Three-dimensional fields of continuous variables including humidity, pressure, temperature and velocity are numerically processed and meteorological features, including weather fronts, are secondary derived properties. A variety of measurements can be input into the numerical model including surface, radiosonde and satellite observations. The water cycle is modelled including the effects of terrain moisture, sea surface temperature, cloud formation and precipitation.

Numerical models can be global or of limited area. Limited area high-resolution models are often termed mesoscale models as they reflect mesoscale meteorological features,weather patterns of less than 100km in size.

The UK Meteorological Office (UKMO) has and makes available so-called Unified Models of mesoscale and global data. The NWP model maps each define a grid over the map's coverage region and the models provide the means of working out tropospheric delays at corresponding points. For example, the UKMO has two NWP models, the so-called global model and the mesoscale model. The former has a horizontal resolution of 0.8333 degrees (5/6 degrees) in longitude and 0.5555 degrees (5/9 degrees) in latitude giving a grid of 432 x 325 points defining the earths surface, each point associated with a cell of about 60km at mid latitudes and about 90km in the tropics. This global map may be used inter alia to provide boundary points for a mesoscale model which is a regional model centred on the British Isles and has a resolution of 0.11 degrees in longitude and latitude (the grid being rotated with a shifted pole to maintain uniform horizontal resolution) and has 146 x 182 grid points which correspond to an array of cells of approximately 12km x 12km. Both models have 38 vertical levels and extend to about 40km.

At any grid point of the relevant map the atmospheric refractive index (and therefore the gradient of the refractive index) can be derived from numerical weather prediction model pressure, water vapour partial pressure and temperature fields. Atmospheric refractivity can be divided into dry (hydrostatic) and wet components. A simple two-

Hydrostatic and wet mapping functions according to the Niell methodology possess a high degree of accuracy without the need for prior meteorological information, and the variation of tropospheric delay with elevation angle can be efficiently modelled by a continued fraction expansion.

Meteorological features that possess a large spatial and/or temporal variation in tropospheric delay will impact the accuracy of NWP-derived tropospheric corrections and the bandwidth required for dissemination on a regional or global basis. The temporal and spatial variation in hydrostatic refractivity is generally small, whereas meteorological features associated with rapid changes in atmospheric moisture significantly impact the accuracy/bandwidth relationship.

Meteorological features smaller than the resolution of the numerical prediction model will not be accurately reflected in the NWP-derived tropospheric correction.

A weather front marks the interface between air masses: defined as a large body of air whose physical properties are largely uniform horizontally for hundreds of kilometres. The front can mark the occurrence of abrupt changes in atmospheric moisture, temperature and therefore refractivity. Fronts can be divided into three classifications: warm, cold and occluded.

The most rapid change in tropospheric delay is likely to occur when satellite elevation and front inclination are equal. Generally, in the UK, frontal systems move at 30 to 50 kilometres per hour and can result in zenith delay variations of 3 cm/hour. Tropospheric delays vary in accordance with inclination to earth insofar as they are described by ray-tracing that is taking place through meteorological features that vary differently with both altitude and position.

The server 200 thus takes as input regional or global numerical weather prediction model information including pressure, temperature and humidity data and computes the

three-dimensional refractive index field from the meteorological data. Wet and dry tropospheric delays are derived for a gridded area, corresponding to the NWP coverage, at heights corresponding to a terrain database (that may be the NWP terrain). These are transformed to, or initially computed as zenith delays for the same grid locations including height, wet and dry zenith delays are computed from the first model 210.

The server, in computing the the difference between first model and meteorological model, and thus the modifications required to the first model zenith delays to make them accurate, derives these differences each as a fractional change from the first model value, as a percentage.

There are two benfits to this. Firstly it is found that notwithstanding the actual values of the delays and the differences, the differences lie in a small range (approximately ± 10%) from the corresponding first model values; this permits developing a smaller range of correction values to transmit than if actual value differences were used. Secondly, it provides for better correction of first model zenith delay values by interpolation.

A correction, $BC_{\%}$, defined as a percentage correction to the first model that includes the variation of zenith delay with height is transmitted. The corrections are in the form of a gridded data set. The user can linearly interpolate their tropospheric correction from the adjacent set points.

$$BC_{\%}(\phi, \lambda, h_0) = 100.\frac{ZD_{nwp}^{h_0} - ZD_{prior}^{h_0}}{ZD_{prior}^{h_0}}$$

where,

$ZD_{nwp}^{h_0}$ is the zenith delay, measured from height h_0, computed from the numerical weather prediction,

$ZD_{prior}^{h_0}$ is the zenith delay, estimated from height h_0 computed using the a priori climate model,

can compile a matrix array of such zenith delay modifications for the various locations of the organisation's map coverage.

For example, as mentioned above, the UKMO has two NWP models, the so-called global model and the mesoscale model. The former has a resolution giving a grid of 432 x 325 points defining the earths surface, and the mesoscale model which is a regional model centred on the British Isles has 146 x 182 grid points.

Thus there exists a two-dimensional matrix array of point correction sets each represented by a multi-bit word. In particular this can as in this embodiment be represented by an 8-bit word.

Thus there exists in the base station, and based upon the particular Unified or NWP model of interest, a geographical distribution of corrections, essentially an 8-bit greyscale map image of the corrections. To the extent that it helps understanding, such a map is capable of being represented visually and Figure 4 comprises such a representation of a global correction map.

Whereas the visual representation is actually of numerical data according to the information and its dissemination, it will be appreciated that the format of the information lends itself to data compression techniques employed with such two-dimensional images in order to reduce the size of the data file or information for dissemination.

A lossless or lossy compression map of data be employed, but in this embodiments the server effects a lossy image compression ; the preferred compression is in accordance with the JPEG2000 standard (wavelet-based) although other standards, such as JPEG (cosine based) or other techniques such as simple sub-sampling may be used, to reduce the file size of the information.

At this point it is appropriate to refer again to the user receiver. Insofar as the correction data signal is received from a GNSS satellite with the usual signals, no special receiving circuitry is needed. The correction (image) data set is passed to processor providing zenith delay computation which decodes the image for use of the

individual pixel values as corrections as described above. Such decoding may be accomplished by a hardware feature built into the receiver or such decoding may be achieved by software loaded into the central processor of the receiver; software for JPEG image file decompression is well known

For example, if the file size of the uncompressed image is about 141 kb a compression factor of 35 (reducing files size to 4kb) indicates little compression noise, but in a greater compression of 140 (to 1kb) compression noise is evident. This is also shown graphically in Figure 5.

It will be appreciated that the conditions for wet delay functions are far more complex and produce greater file sizes than dry delay functions. Thus separating wet and dry delay functions which can reasonably expect compressed file sizes of the order 9 kb and 1 kb respectively, there is need to disseminate about 88,000 bits.

This data set may be transmitted as a single image to all satellites of a constellation group. In this embodiment, the ability to effect data transmission at such a low rate is achieved by effecting the transmission to the GNSS satellites, with the full images at high transmission rate / long duration or only part of the image associated with the map region associated with a particular satellite or split amongst the satellites for each to receive only the part related to it, permitting a further factor of three reduction in required reception time; that is, transmission and reception would take about 2 minutes at a data rate of 250 bits/sec.

Thus each of the GNSS satellites is able to broadcast, with the normal signals, correction signals that each user receiver can employ with the zenith tropospheric delay modelling, to effect a correction to values employed with the model, in accordance with substantially current meteorological conditions pertaining to its location.

It will be appreciated that the rate of data dissemination is of both technical and economic importance. Firstly, the data transmission capacity available for slotting in the additional information is limited, at least in current implementations of GNSS.

Whereas for other types of data the solution may be to prolong the duration of the transmission event, in the case of updating weather dependent data this is not a suitable option. Insofar as weather changes and weather features move over the earth's surface and thus the grids employed in the meteorological model, there is a currency element, that is, a time interval and/or distance for which a desired tropospheric delay value is valid. It is believed that such currency time is of the order of one hour and/or grid size of 50 to 90 km. Thus, if a user is to rely upon meteorologically generated tropospheric delay values (by way of a correction) it should be within such validity time or position for which generated. Thus, in terms of transmission to a user, transmission must be at such a rate that the user can receive and process the information while it is still valid. Satellite transmission rates are both slow in bit rate and intermittent in availability for downloading such correction information. Thus, there is an imperative to effect a data reduction to accommodate transfer of a correction data (image) set whilst the data retains viability.

Furthermore, the time taken to download the correction data (image) set should not be unduly long as to cause the user to decline to wait for the time it takes to effect the download, decompress the image data file and compute position.

Thus, it is important to effect the degree of data reduction/image compression that achieves these various objectives.

Having regard to the above discussion of viability of delay values (and derived corrections) it should be noted that employing data based on NWP model approach it is in practice possible to predict the weather conditions and derive tropospheric delays for any given point in advance, up to several hours, notwithstanding that the viability of predicted tropospheric delay is relatively small (as described above) once current at the predicted time.

Therefore, it is possible to develop not only a set of tropospheric delays (as Zenith tropospheric delays) associated with a region's grid points but also to develop

altitude (c). These may also be corrected by correction sets derived in the server. This mapping function may be expressed as:

$$m(\varepsilon, a, b, c) = \frac{1 + \cfrac{a}{1 + \cfrac{b}{1 + c}}}{\sin(\varepsilon) + \cfrac{a}{\sin(\varepsilon) + \cfrac{b}{\sin(\varepsilon) + c}}} \qquad (2\text{-}1)$$

where ε is the elevation angle.

This may be further expressed as:

$$m(\varepsilon,a,b,c) = \frac{1 + \cfrac{a_0 + \Delta a}{1 + \cfrac{b_0 + \Delta b}{1 + c_0 + \Delta c}}}{\sin(\varepsilon) + \cfrac{a_0 + \Delta a}{\sin(\varepsilon) + \cfrac{b_0 + \Delta b}{\sin(\varepsilon) + c_0 + \Delta c}}} \qquad (2\text{-}2)$$

where a_0, b_0 and c_0 are the first model values and Δa, Δb, Δc are corrections to be applied thereto to effect mapping of elevation derivable by the meteorological model.

By a fitting process operated such that sum of the squares of the residuals between the equation (2-2) and the ray traced (truth) is minimised, a set of correction values may be derived composed of Δa, Δb and Δc as a similar data image file or superimposed upon the Zenith correction data image file by increasing the word length thereof to include word elements comprising these corrections.

Transmission and reception coding and decoding is as before except that the receiver now has correction values to employ with the parameters of the mapping function whereby both the Zenith delay and its map values are more accurately represented.

It will be appreciated that it is possible to include in elevation mapping functions the parameters of longitude and time of day, and the above approach to deriving a numerical solution therefor may be extended thereto.

Although it is convenient and in many ways advantageous to employ NWP, other meteorological sources may be used on combination therewith to augment the data available. Any other meteorological model that takes a three dimensional view of the atmosphere may be employed instead of the NWP. As will be appreciated, the NWP derives tropospheric delays are defined for a grid having a cell size limited by the NWP model in use. Many weather features that have a high moisture content and can effect tropospheric delay, such a thunder storms, may be below the resolution threshold of the NWP model. However, there exists a number of sources of data such as satellite images of an essentially dimensional nature that can identify with high resolution the existence of such features and the information contained therein can be employed to vary the NWP values for a particular cell of the grid to take such features into account across the NWP grid.

The above described embodiment is intended to enable a user receiver having a built in first, non-meteorological model to determine its position more accurately than is possible by use of the model alone. It will be appreciated that part of the computation solution is to derive a time value to the accuracy permitted by the model's interpretation of tropospheric delay. For some users, it is the time function that is of importance and such user may know the precise location of a fixed receiver.

Referring to Figure 6, this shows a schematic representation of a second embodiment of GNSS 500. A user receiver 520 is similar to the user receiver 120 but lacks (or has disabled) the first, non-meteorological model.

CLAIMS

1. A method of obtaining tropospheric delay data for use in a satellite positioning system or GNSS by a user at a location comprising the steps of generating at a location remote from the user location, from meteorological information, at least one accurate tropospheric delay value applicable to the user location and either, with knowledge of the user position, generating said at least one accurate tropospheric delay value for the known user location for communication as a correct tropospheric delay value to said user, or without knowledge of the user location, generating at least one tropospheric delay value presumed by a user to be applicable at a said unknown location then determining from the accurate and presumed tropospheric delay values a correction applicable to the presumed tropospheric delay values for communication as a tropospheric delay correction to a said user.

2. A method of obtaining tropospheric delay data for use in a satellite positioning system or GNSS by a user comprising generating at a location remote from the user location, from a first model which is known per se, a first set of approximate tropospheric delay values applicable to various user geographical locations, generating from a meteorological model employing meteorological information a second set of tropospheric delay values that are accurate and applicable to said various user geographical locations, developing a set of delay value modifications for use with said first model so that the first model can provide a set of tropospheric delay values substantially in agreement with the second set, and expressing the set of modifications as a set of tropospheric delay corrections for communication to a said user.

3. A method according to claim 2 wherein the first model is based on non-meteorological parameters.

4. A method according to claim 3 wherein said non-meteorological parameters comprise at least one of time of year, latitude and altitude.

5. A method according to claim 4 wherein said non-meteorological parameters comprise at least one of longitude and time of day.

6. A method according to any one of claims 2 to 5 wherein said sets of tropospheric delay values comprises zenith tropospheric delays.

7. A method according to claim 6 wherein the first model contains a mapping function relating tropospheric delay at a given elevation angle to the zenith tropospheric delay.

developing a prediction set of said corrections for said geographic region of the earth's surface, whereby each member of said prediction set describes a correction that becomes current as a function of time from development.

29. A method according to any one of the preceding claims comprising communicating the correction or set of corrections to a remote user on a communication channel or data link.

30. A method as claimed in claims 29 when dependant claim 28 comprising communicating said prediction set of corrections as a batch and using members of the set as the time for which each was predicted becomes current in respect of the forecast.

31. A method according to claims 29 or 30 comprising communicating at least part of the corrections to at least one orbiting satellite and re-transmitting at least part of the set to a user from a said orbiting satellite.

32. A method according to claim 31 comprising communicating the corrections to at least one orbiting GNSS satellite from which user receives signals to establish at least one of position and time.

33. A method according to claim 31 or claim 32 comprising communicating to a said satellite for re-transmission of only that part of the correction data that can be of use to a user in a region within range of said satellite.

34. A method according to any one of claims 31 to 33 when dependant on claim 30 comprising communicating said prediction set of corrections to said at least one orbiting satellite in a batch and re-transmitting the members one at a time as the time for which each was predicted becomes current in respect of the forecast

35. A method according to any one of claims 31 to 34 comprising applying data reduction sufficient to permit transmission of all or part of a said corrections useable by a user within a time, dictated by transmission availability and

transmission rate of the satellite, substantially lower than the validity time of the meteorological information used in determination of said corrections.

36. A method according to claim 35 wherein the data reduction is arranged to permit transmission of a said corrections to a user corresponding to a meteorological temporal resolution of said meteorological information of no greater than 1 hour.

37. A method according to claim 35 or claim 36 wherein the data reduction is arranged to permit transmission of a said corrections to a user corresponding to a meteorological spatial resolution of said meteorological information of no greater than 50 km.

38. A method according to any one of claims 35 to 37 wherein the data reduction is arranged to permit correction data transmission to a user at a data rate in the range 25 to 500 bits/s.

39. A method according to claim 38 wherein the data reduction is arranged to permit correction data transmission in the range 200 to 250 bits/s.

40. A method of correcting tropospheric delay errors in a GNSS receiver having means to derive modelled tropospheric delay values from non-meteorological parameters, the method comprising obtaining data in accordance with any one of claims 2 to 18 or any one of claims 21 to 39 dependant thereon as a set of corrections, by the use of a first model corresponding to the model in the receiver, remotely of the receiver and transmitting said set of tropospheric delay value corrections, receiving said corrections in the GNSS receiver and modifying tropospheric delay values obtained by use of the receiver modelling means in accordance with the received corrections.

41. A method according to claim 40 comprising determining within the receiver, from the non-meteorological parameters and the model, an approximation to tropospheric delay values and therefrom an approximate position of the receiver relative to the earth's surface, and deriving tropospheric delay value modifications

location for communication as a correct tropospheric delay value to said user as said function for transmission or, without knowledge of the user location, generating at least one tropospheric delay value presumed by a user to be applicable at a said unknown location then determining from the accurate and the presumed tropospheric delay values a correction applicable to the presumed tropospheric delay values as said function for transmission.

46. Apparatus as claimed in claim 45 wherein said meteorological information is arranged to derive a set of tropospheric delay values applicable to a plurality of user locations.

47. Apparatus for obtaining data for use by a user of a satellite positioning system or GNSS, comprising first generating means for generating a first set of approximate tropospheric delay values applicable to a plurality of user locations from a first model which is known per se, second generating means for generating a second set of more accurate tropospheric delay values applicable to said plurality of user locations from a meteorological model based on meteorological information, developing means for developing from said first and second delay sets a set of tropospheric delay value modifications for use with said first model so that it can provide a set of tropospheric delay values substantially in agreement with the second set, said developing means being arranged to express the modifications as a set of tropospheric delay corrections, and means to communicate at least some of said tropospheric delay corrections to the user.

48. Apparatus as claimed in claim 47 wherein said first generating means utilises a said first model is based on non-meteorological parameters.

49. Apparatus as claimed in claim 47 or claim 48 wherein the developing means is arranged to express said set of corrections each as a difference between corresponding values of the first and second sets.

50. Apparatus as claimed in claim 47 or claim 48 wherein the developing means is arranged to express said corrections a fractional change from the values to be corrected.

51. Apparatus as claimed in any one of claims 47 to 50 wherein the developing means is arranged to express the corrections as a distribution over a region of the earth's surface.

52. Apparatus as claimed in claim 51 wherein said region is global.

53. Apparatus as claimed in claim 51 or claim 52 in which the developing means is arranged to express the corrections in the form of a data file of a greyscale image of multi-bit words, each word representing a location of the region.

54. Apparatus according to any one of claims 47 to 53 including means for compressing said set of corrections.

55. Apparatus according to claim 54 in which the means for compressing said set of corrections comprises means to effect lossy compression on the set.

56. Apparatus according to any one of claims 47 to 55 comprising transmission means for transmitting said set of corrections to a user via an orbiting satellite.

57. Apparatus as claimed in claim 56 arranged to transmit to an orbiting satellite corrections for re-transmission to the user from that satellite and to transmit only corrections applicable to users in regions served by satellite.

58. Apparatus as claimed in claim 45 or claim 46 wherein the apparatus is arranged to receive from the user information defining at least one of the user location with respect to the server or with respect to the GNSS satellites.

59. A GNSS user receiver comprising means operable to generate from an on-board model from non-meteorological data approximate tropospheric delay values applicable to identification signals received from a plurality of GNSS satellites and from said delay values compute an approximate position of the receiver

relative to the earth's surface or time, means operable to receive a set of corrections to said approximate tropospheric delay values derivable from the model, said corrections being derived from meteorological data, means to effect modifications to said generated delay values in accordance with the corrections and means to compute the position or time with greater accuracy.

60. A GNSS user receiver as claimed in claim 59 wherein said means to effect modification to said delay values is operable to effect interpolation or extrapolation of said corrections according to computed position of the user relative to locations for which the corrections have been derived

61. A GNSS including a plurality of orbiting satellites, apparatus as claimed in any one of claims 45 to 57 and a user receiver according to claim 59.

62. A GNSS including a plurality of orbiting satellites, apparatus as claimed in any one of claims 45 or 58 and a user receiver at a location known with respect to the apparatus.